Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy

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Journal:	*Part A: Journal of Power and Energy*
Manuscript ID:	JPE-14-0326.R2
Manuscript Type:	Special Issue on Renewables
Date Submitted by the Author:	n/a
Complete List of Authors:	Adams, Charlotte; Durham University, Earth Sciences Auld, Alison; Durham University, Engineering and Computing Sciences Gluyas, Jon; Durham University, Earth Sciences Hogg, Simon; Durham University, Engineering and Computing Sciences
Keywords:	Geothermal power, Heat, Power, Energy, Low, High, Enthalpy
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Geothermal Energy – the Global Opportunity

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Abstract

Exploitation of geothermal energy offers a consistent and secure low carbon energy supply. Geothermal energy resources are associated with a variety of geological settings, are available at temperatures ranging from a few tens of degrees to several hundred degrees and may be used for the provision of heat, power or both. Their exploration, assessment and exploitation draws from a wide range of techniques. Improvements in deep drilling and energy conversion technologies mean that many countries could develop geothermal energy systems. There are both economic and technical risks and challenges associated with geothermal energy exploitation, however the potential for geothermal resources to provide low carbon and continuous power, heat or both means they have the potential to be an increasingly important part of the energy mix for many areas of the globe.

Keywords

Geothermal, energy, heat, power, low, high, enthalpy

Introduction

Global geothermal energy resources are significant; the theoretically extractable geothermal heat in place within the upper 5km of the earth is estimated at 140x10^6 EJ[1]. Less than one percent of this resource is currently tapped although geothermal energy has been exploited for millennia[2], beginning with the use of hot springs for heating, bathing and mineral extraction. In 1913, Larderello, in Italy became the first operational geothermal power plant[3] and the Wairakei field in New Zealand has operated since the early 1960s[4] demonstrating the longevity of geothermal systems. Geothermal energy can be exploited to produce electricity[5] or used directly for heat. Globally, 48.5 GW of geothermal energy is used directly for heat, as of 2010[2], while 12 GW is converted into electricity[6]. China is the largest user of geothermal heat and the USA is the largest producer of geothermal power. Geothermal plants have a relatively small surface footprint and can provide a source of secure, low carbon energy that is more controllable and less intermittent than alternative low carbon energy systems such as wind and solar and as such is a good base load energy source.

Geothermal energy is derived from heat flow from the earth's core and naturally occurring radioactive decay occurring within the Earth's interior. It is distinct from ground source heat that is located within the upper few 100m of the surface and is attributed to solar warming. Successful exploitation of geothermal energy relies upon effectively handling geothermal aqueous fluids that may be volatile, corrosive or contain environmentally sensitive chemical constituents[7]. Geothermal resources are broadly classified by temperature as high (above 150^{o}C) or low (below 85^{o}C) enthalpy[8]. High enthalpy resources are capable of producing heat and power and are generally associated with tectonically active regions while low enthalpy resources are most often exploited solely for the production of heat and are located in more tectonically quiescent settings and these settings account for the majority of geothermal potential yet to be exploited[6]. The economic case for exploiting low enthalpy resources is less attractive than for high enthalpy resources because of the lower resource temperature and the fact that heat is less portable than power. Ideally, for heat, the end user should be located near the resource. Most of geothermal power production uses naturally generated steam to drive turbines hence the 150^{o}C cut-off reported above. However, improvements in organic Rankine and Kalina power cycle technology are facilitating the generation of power from ever-lower temperatures. Currently, the lowest resource temperature at which organic Rankine cycle technology has been used for power generation is 72^{o}C at the Chena Hot Springs Resort, Alaska[9]. Geothermal systems are further categorized by their geological setting into four types, hydrothermal convective systems, molten or magma systems, hot aquifers and enhanced geothermal systems. This paper will review some of the engineering challenges associated with the exploitation of and generation of energy from each type of setting.

Geothermal Settings

Hydrothermal convective geothermal systems are associated with tectonically active areas and most are restricted to tectonic plate boundaries. Hydrothermal systems are so-called because meteoric water enters the subsurface via natural cracks and fissures whereupon it becomes heated by a magmatic source. The circulation path of these systems can be up to 8km[4] and as the water descends and becomes heated, it then convects upwards to surface. The Geysers in California provide an example of a hydrothermal setting, which provide over 90% of all geothermal power production[4]. Generally, these systems are of high temperature and the need to circulate fluids by pumping is negated but fluid injection may be necessary to maintain steam production. High enthalpy systems can be volatile and produce greater quantities of gases such as CO_2 and H_2S leading to increased associated carbon emissions and undesirable odours[10] respectively.

Exploitation of molten resources (magma) involves drilling into molten rocks or magma chambers and is at the experimental stage[11, 12] although these systems may offer the highest temperatures and offer greater power generation potential, they also carry the highest risk associated with their high temperatures, production of volatile (unwanted) compounds, lack of suitable materials and lack of suitable heat transfer fluids.

Hot aquifers are geological formations which are capable of both storing and transmitting fluids and can be found in sedimentary basins that have insulating overburden. The continuity of such aquifers may be extensive (covering areas of several km^2) and many are permeable. Where deeply buried (depths of >2 km) the temperature of these low enthalpy resources is likely to be in excess of around 60 ^{o}C (typical thermal gradients over much of the Earth[2] are 20-30 ^{o}Ckm^{-1}). Hot aquifers are compatible with district heat networks and are currently being exploited in China[13], Paris[14], Hungary[15], Germany[16] and the UK[17]. For nations reliant on fossil fuels for heating, they have the potential to reduce carbon emissions by offsetting heat demands and provide an indigenous, secure energy supply.

Engineered or enhanced geothermal systems (EGS) or hot dry rock systems as they are sometimes called, exploit emplaced radiogenic granitic bodies at depths of 3-5km from which there is no natural emission of hot water or steam because the host rock is generally impermeable and there is little or no heat transfer fluid. The recovery of geothermal energy relies upon increasing the permeability of the granite to improve reservoir properties and facilitate the circulation of fluids through the hot rocks. Garnish[18], summarises the ideal properties for an EGS reservoir (Table 1).

Fluid production rate	50-100kg/s
Fluid temperature at wellhead	150-200^{o}C
Total effective heat exchanger surface	>2 x 10^{6} m^{2}
Rock volume	>2 x 10^{8} m^{3}
Flow impedance	<0.1MPa/(kg/s)
Water loss	<10%

Table 1: Ideal EGS reservoir properties[17]

The permeability of these systems has often been increased by hydraulic fracturing which then allows cold water to be injected into the fractured reservoir to become heated and returned to surface[19, 20]. The produced hot water or wet steam is then passed through a binary plant for power production. The longevity of geothermal EGS systems is currently unproven but has been extensively modelled and is expected to be on the scale of decades, however thermal output will generally decrease with time[21]. The key factor affecting well longevity being the recovery factor or the fraction of extractable heat available at any particular time. The recovery factor is linked to the duration of thermal energy extraction and rate of replacement from radiogenic processes, operational increases in permeability created by thermal fracturing following re-injection of cooler water and other permeability changes caused by mineral dissolution or deposition during operation. The Soultz project[22] and Landau[23] plants are well documented examples of EGS systems.

Heat distribution and thermal gradients

The geothermal gradient describes the increase in temperature with increasing depth below surface. The average global geothermal gradient is 20-30^{o}C/km[24]. Existing geothermal energy systems generally exploit areas where the geothermal gradient is enhanced. The factors that locally increase geothermal gradients include proximity to tectonically active regions for example at plate margins where the Earth's crust is being created (e.g. Iceland) or destroyed (e.g. Indonesia) and the production of radiogenic heat. Recent literature has highlighted the importance of ensuring that heat flow data has been corrected for palaeoclimate and topographic effects to assist in making more accurate predictions of temperatures at depths outwith measured ranges[25, 26]. Failure to do this can underestimate the potential of geothermal resources and affect the economic viability of proposed schemes by overestimating the depth of drilling required.

Radiogenic heat leads to higher heat flows due to the decay of uranium and thorium contained within intrusions of igneous rocks (e.g. granite) that have risen from a magmatic source and become emplaced within the Earth's crust (they may or not be exposed at surface) e.g. the North Pennines in the UK[27] and the Cornubian Batholith[28]. Their relative buoyancy relative to their host rocks leads to uplift, the response to this being the development of faults. There is evidence that faults associated with igneous intrusions can act as conduits for geothermal fluids acting over scales of km[29]. Crustal thinning in extensional sedimentary basins also leads to higher heat flows due to the convection of heat from the mantle. The latter two settings are generally most productive when there is a thick blanketing layer comprising several km of sedimentary sequence that have low thermal conductivity covering the target formation.

Generation of heat and power

Geothermal resources can be generally divided into three groups based on the temperature of the geothermal resource available. Table 2 shows the temperature ranges used to categorise geothermal resources. These are determined by what energy conversion technologies are feasible at different temperatures. The temperature and hence fluid phase and flow rate of resource determines the methods of conversion into power. In general terms, power generation uses water at temperatures exceeding 150^{o}C, the lowest temperature from which geothermal power is generated is 72^{o}C at Chena Hot Springs in Alaska[8].

Low Temperature (< 85^{o}C)	Moderate Temperature (85 - 150^{o}C)	High Temperature (> 150^{o}C)
Direct Use (heat)	Direct Use (heat)	Flash Steam Power Plants Binary and combined cycles
Heat Pump	Binary Power Cycles	Dry Steam Plants Binary and combined cycles

Table 2. Energy conversion types appropriate for different grades of geothermal energy[30].

High Temperature Geothermal Resource Conversion Technologies

Traditional geothermal exploration has focussed in settings with very active tectonic plate boundaries[31]. In these regions there is magmatic activity very close to the earths surface and therefore geothermal resources from these regions are high temperature. High temperature geothermal resources were targeted first in the development of geothermal energy because they are the most economically attractive and because many use traditional power plant technology, similar to fossil based generation plant that has been adapted to cope with more geochemically aggressive geothermal steam. This means dry and flash steam power plants fuelled by geothermal heat are mature and known technologies.

The key difference between dry steam and flash plants is a dry plant will have superheated vapour at the wellhead, while for a flash plant it will be a saturated two phase liquid. Dry steam power plants are the most simple for power generation. Mechanical work is generated by driving steam from the wellhead directly through a turbine, this is then converted to electricity by a generator as shown in Figure 1[32].

Flash power plants operate with geothermal fluids at temperatures of 150^{o}C to 350^{o}C. The geothermal fluid is turned into steam, via a flash vessel, which then turns a turbine in the same manner as the dry steam plants, Figure 1. If the brine has low dissolved solids and if increased energy extraction is required then after the first turbine, the fluid can be passed into another flash vessel to drive another turbine and extract further energy, known as a double flash.

Most recent data show dry steam plants account for 27 % of installed capacity and flash power plants produce 61 %. Table 3, the remainder can be attributed to double flash and binary plants. Cost estimations for geothermal projects vary widely depending on the resource type, power plant technology and remoteness of the site but in literature costs, for high temperature geothermal power plants, range from 2.8 to 5.5 million $/MW[33].

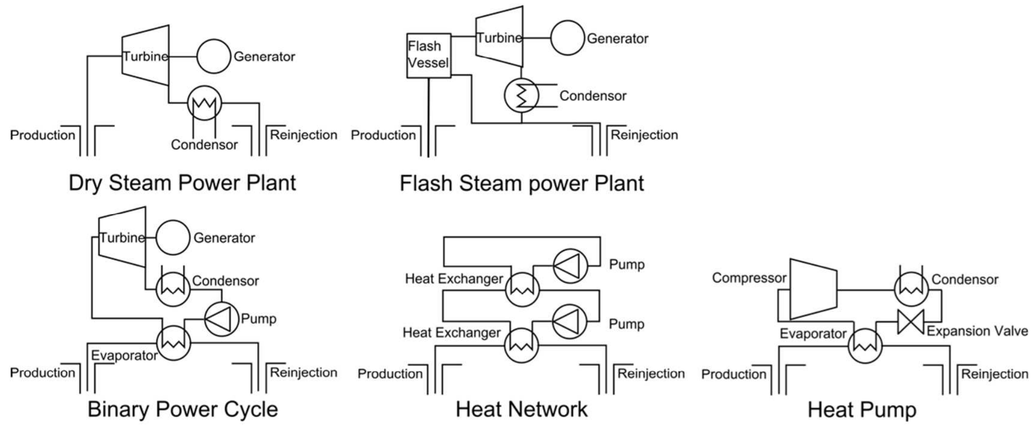

Figure 1. Schematic diagram of geothermal conversion technologies[32]

Plant type	Units	Installed capacity MW	Average size MW	Percent
Dry steam	62	2878	46	27
Single Flash	141	4421	31	41
Double Flash	61	2092	34	20
Binary	236	1178	5	11
Back Pressure	25	145	6	1
Total	526	10715	24	100

Table 3. Global distribution of geothermal power plants by type, 2010 data[34]

Low and Moderate Temperature Geothermal Resource Conversion Technologies

Moderate temperature hydrothermal reservoirs are anticipated to make the largest contribution to increase global geothermal power production in the future[32]. Moderate temperature geothermal energy may be converted to electricity through binary cycles or used directly as heat. A dramatic increase in the exploitation of moderate temperature geothermal energy was predicted by several studies[32,35]. Younger[31], asserts that the predicted increase in geothermal power production has not occurred due to poor geological understanding. Low and medium enthalpy reservoirs are more costly to develop because heat output per well is lower and power generation is less efficient therefore more drilling is required per unit of power production. Quoilin *et al*,[36] report the costs of a geothermal organic Rankine Cycle (ORC) plant as 7250 - 3000 €/kW for plants of 200 - 35000 kW respectively. The increased cost of an ORC plant, when compared with dry steam or flash plants combined with larger drilling costs, and lower power outputs currently results in the cost of low enthalpy geothermal projects often being unfeasible.

Despite their proportionally low uptake, binary power plants comprise of 12.3 % of geothermal energy production although may use high temperature resources[37]. The operation of an ORC is shown in Figure 1, the working fluid may be selected to complement the geothermal resource temperature allowing these cycles to operate over a range of temperatures.

Low temperature and some moderate temperature resources are used directly as heat supplies. Geothermal heat is transferred to water in a distribution circuit via heat exchangers; heat exchangers are then also used to transfer the heat energy into building heating or hot water circuits for use[38]. This is shown in Figure 1. Heat exchangers and insulated pipes to transport the hot water are known and mature technologies. Heat network cost depends upon the proximity and density of heat loads. An indicative cost of a heat network in an urban environment is 1.5 million €/ km[39].

Where the temperature of a geothermal resource is not high enough to be used directly, heat pump technology is used, this accounts for 45% of geothermal heating schemes[2]. Additional mechanical energy is used to compress a refrigerant heated by the geothermal source; this means the heat supplied by the heat pump when the working fluid is condensed is the sum of the geothermal and mechanical energy. A schematic diagram of a heat pump is shown in Figure 1. Maintenance costs for heat pumps are minimal compared with the capital cost which is approximately 1200 - 1600 €/kW. Self et al.[37] note that the feasibility of heat pumps varies with the climate into which it is installed. In a hot country with low heat demands the high capital costs are of greater significance compared with existing heating costs.

Risks and R&D Challenges

There are a wide range of risks and challenges associated with deep well drilling and the economic production of geothermal heat and or power.

Geochemistry

Geothermal fluids are often referred to as brines because they may contain a range of dissolved minerals due to having been in contact with host rocks at high temperatures within the Earth's crust and there are clear geochemical differences between low and high enthalpy geothermal fluids[7] due to differing fluid/host rock interactions one difference being that high enthalpy fluids generally contain more silica. In some areas, geothermal fluids are "mined" for the elements they contain[38]. Managing potentially highly saline fluids that may also contain gas can be a further challenge having developed a geothermal reservoir as their composition may change following changes in pressure and temperature during the process of energy extraction[7]. The presence of some dissolved constituents can heighten environmental concerns associated with the mobilisation of elements from the target formation at depth to higher levels because they have the potential to threaten aquifers or contaminate surface waters. Thermal and chemical contamination of overlying aquifers has occurred in the Balcova Geothermal Field (Turkey) resulting in the presence of elements such as arsenic, antimony and boron within shallower groundwaters. Summers et al.[40] outlined a methodological framework for identifying groundwater contamination from geothermal energy developments. Where fluids are injected into geothermal systems either for EGS systems where the reservoir is naturally dry because of the host geology or in high enthalpy systems where additional fluid injection is required to maintain steam production this has an impact upon geochemistry and can make the resulting geothermal fluids easier to handle by diluting some of their chemical constituents.

Well Failure

Geothermal wells are drilled in the depth range 1.5km to 5km, at greater depths, temperatures and pressures, engineering challenges increase. Possible sources of well barrier and integrity failure of geothermal wells include loading from the surrounding rock formation, mechanical damage during well development, corrosion and scaling from geothermal fluids, thermal stress, metal fatigue and failure, and expansion of entrapped fluids[41]. The mixing of deep geothermal fluids with shallow groundwaters can occur via natural mechanisms, such as natural upward fluid convection along fault lines (e.g. within the Larderello geothermal field, Italy)[42], and by anthropogenic activities including uncontrolled discharges to surface waters, faulty injection procedures (e.g. Los Azufres, Mexico[43]), and accelerated upward seepage from failed casings within wells and boreholes. Casing failures related to inconsistencies in casing cementation have been cited as one common cause of failure[44]. The major failures of several geothermal wells on the island of Milos, Greece, were attributed to thermal stresses on the well casing that were exacerbated by poor cementation[45].

The International Finance Corporation produced a global study of 2613 wells that found that on average, 78% of geothermal wells drilled were successful (i.e. resulted in geothermal energy output). This report noted an increase in success rates at each site from 50% initially to 70-80% during the operational phase as site experience increases. Failure rates are expected to vary due to the wide range of geological settings from which geothermal energy can be exploited, with volcanically active regions carrying higher levels of risk than more tectonically quiescent regions and sedimentary basins having the highest success rates. Reservoir management is an important part of any geothermal system[46] and Aksoy et al.[47] recommended regular inspection and maintenance of geothermal wells and this is now a statutory requirement in many countries that produce geothermal energy. Decreased pressure and temperature can affect geothermal reservoirs following a period of production, however this can be counteracted by the drilling make-up wells during plant operation[48]. For example at the Geysers, 30 years of geothermal production has reduced the fluid volume in the reservoir however appreciable quantities of available heat remain within the reservoir. Injection of treated wastewater and the drilling of additional make up wells to maintain production has successfully slowed the decline in output while increasing steam production[49].

Fluid flow

A key challenge in geothermal prospecting is the identification of a target formation at a sufficient depth to have a useful temperature that is also capable of storing and transmitting geothermal fluids. This is important for both the abstraction and reinjection of geothermal fluids. For high temperature geothermal fields 20-100 wells may be used and the normal configuration for low enthalpy geothermal areas comprises a well doublet (where separate abstraction and re-injection wells are drilled). EGS systems by their nature may require stimulation by hydraulic or thermal fracturing to increase the permeability of the igneous geothermal target. Although this may challenge the social acceptance of geothermal energy this can be put into context by the fact that the oil industry has routinely used hydraulic fracturing both offshore and onshore over a period of decades[50]. However, unlike the transient production of petroleum from a fracture stimulated well, those drilled in geothermal systems are likely to produce geothermal fluids for decades. In addition, stimulation of geothermal wells generally requires no propant and few chemicals. High enthalpy hydrothermal steam systems e.g. the Geysers may require injection of additional fluids to sustain steam generation, injection of cooler fluids has been assigned as the main reason for micro-seismicity at this site. However fluid injection at this sites helps energy recovery by diluting the effects of some of the naturally occurring elements that have the potential to cause scaling and corrosion. Where there is insufficient reservoir permeability, a single well system may be used where the return pipe is nested within the flow pipe. The predominant mechanism for heat transfer in a single well system is conduction (rather than convection which is the dominant mechanism for the doublet configuration) therefore single wells are generally used for heat only schemes having outputs of a few 100kW which are around one tenth of the output expected from a doublet system where geothermal fluid is circulated[51].

Induced Seismicity

Effective exploitation of geothermal energy depends upon a sufficient flow of geothermal fluid, it may be necessary to increase the amounts of fractures and fissures in a geothermal reservoir to improve its hydraulic properties, this is especially pertinent for buried granite targets. The process of fracturing during initial reservoir stimulation as well as the reinjection of cooler spent geothermal brine can cause thermal fracturing due to contraction of fracture surfaces within the reservoir that may induce microseismicity and cause earthquakes[52]. Microseismicity is not uniquely linked with the production of geothermal energy, is associated with the exploitation of other conventional (e.g. oil, gas and coal) and unconventional (tight gas and shale gas) earth hosted energy sources and has been successfully managed in many environments[53]. It is an important tool for reservoir management however it can be socially unacceptable near to populated areas. Unacceptable surface affects and levels of microseismicity (up to magnitude (M_L) 3.4) led to the abandonment of geothermal well stimulation in Basel in 2006[54].

Water injection is a key process for inducing microseismicity because of increases in pressure in rock pores leading to a reduction in the effective strength of the rock mass[55]. This can decrease static friction and initiate seismic slip. The magnitude, nature and timescale of induced seismicity is controlled by the fluid injection rate and quantity, orientation of existing stress fields and extent and distribution of pre-existing faults and fractures. Seismic events may initially peak then decline as injection rates stabilize or continue after reservoir development and injection[53]. In the example of the Geysers high enthalpy field in California, USA, measured microseismic events have a strong correlation with both water injection and steam extraction[56].

Conclusions

Exploitation of geothermal energy can contribute towards base load energy demand due to its high capacity factors (at least 90%). This makes geothermal energy highly desirable in comparison with other forms of renewable energy such as solar or wind. The method by which geothermal energy may be used is dependent on the following factors: available geothermal resource, distance of resource from heat demand, or power generation network and economic subsidies. Exploitation of low and moderate temperature geothermal energy resources currently requires economic support via subsidies to be feasible. In contrast high temperature geothermal power plants are more mature and less expensive so generally do not require economic support.

Geothermal energy projects are perceived as being risky because significant financial commitment is required when uncertainty about resource viability is high[57]. Also protracted lead times can lengthen the period before financial returns are made. There are several ways the cost and risk of geothermal projects may be reduced. For example, the depth of the well may be selected to make a geothermal project feasible. A deeper well will provide a hotter geothermal resource. Therefore, a project may decide to accept higher drilling costs and drill deep enough to produce electricity from the resource. Many studies have proposed using abandoned oil wells, or those that co-produce hot water, for geothermal schemes[58,59]. This negates the high costs and risk incurred from drilling, but is yet to be widely implemented.

Although the exploitation of geothermal energy is not without its challenges there is a diverse array of available resources from which it can be produced in many regions of the globe and improvements in drilling and power generation technology serve to increase the available resource base.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgements

The authors thank the anonymous reviewers who provided constructive feedback and suggestions that have improved this article. This article is a contribution to the BritGeothermal research partnership.

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